07 - 10 September 2009

PROCEEDINGS

54. IWK

Internationales Wissenschaftliches Kolloquium

International Scientific Colloquium

Information Technology and Electrical Engineering - Devices and Systems, Materials and Technologies for the Future

Faculty of Electrical Engineering and Information Technology

TECHNISCHE UNIVERSITÄT ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c.
Peter Scharff

Redaktion: Referat Marketing
Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
Univ.-Prof. Dr.-Ing. Frank Berger

Redaktionsschluss: 17. August 2009

Technische Realisierung (USB-Flash-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag: isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

ISBN (USB-Flash-Ausgabe): 978-3-938843-45-1
ISBN (Druckausgabe der Kurzfassungen): 978-3-938843-44-4

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=14089

AIRGAP OPTIMIZATION FOR SMOOTHING INDUCTORS FOR DC OUTPUT POWER CONVERTERS

Lucian Mandache, Dumitru Topan

University of Craiova, Electrical Engineering Department,
107 Decebal Blv., Craiova-200440, Romania
lmandache@elth.ucv.ro; dtopan@central.ucv.ro

ABSTRACT

The paper is focused on an optimization tool for smoothing inductors for DC output power converters, in order to set up the airgap for the best smoothing effect in any given working conditions. Such situation appears frequently in practice, being solved usually in approximate manner or through tediously repeated experimental essay. The optimization tool is based on time domain numerical simulation with an accurate model of the ferromagnetic core, which considers the nonlinearity, iron losses and the electromotive force of the eddy currents. This model is part of the whole circuit, containing the power network, the DC output converter and the load. It is implemented with the powerful circuit simulator SPICE.

Index Terms – Nonlinear inductor, numerical simulation, optimization, objective function, time domain circuit analysis

1. INTRODUCTION

The nonlinear saturable inductors are capital components of power converters. Because of the strongly distorting regimes, often with a significant DC component, the ferromagnetic core of a filter inductor works on minor hysteresis loops that strongly modify the dynamic permeability and the dynamic inductance.

Their optimal design depends on the power converter characteristics and, equally, on the load. In practice, for a given DC output power converter, e.g. chopper or rectifier, with a smoothing inductor of the load current, the best smoothing effect is obtained as a result of an optimal setting of the inductor airgap, which strongly depends on the level of the load. The most effective way to solve such a problem is, indubitably, through a numerical analysis that is able to provide the optimal value of the airgap.

In order to achieve this requirement, the simulation tool must consider the global diagram: network - power converter - nonlinear inductor - load. The nonlinear phenomena in the ferromagnetic core (B-H characteristic, eddy currents, iron losses), requires an accurate model of the inductor, coupled to the external electric circuit. We developed such a model, which overcomes other approaches, often based on approximate formulas [1-4]. It takes its mathematical root from the Maxwell's theory and can be easily included in a time-domain circuit simulator, like SPICE [5,6]. The model has been successfully verified on many applications, one of them being presented here.

2. SIMULATION PRINCIPLE

The main component in our optimization tool is an accurate time-domain model of the ferromagnetic core, which we recently developed and validated using experimental tests and alternative analysis tools [5-8]. It is shortly described bellow. It is widely known that the simplest lumped model of a homogenous path of a linear magnetic circuit is a linear electric resistance, numerically equal to the magnetic reluctance. In such manner are modeled the airgap magnetic reluctances and those corresponding to leakage paths. The nonlinearity of the magnetic material is easily modeled through a voltage controlled nonlinear resistance. The current of the resistance is numerically equal to the magnetic flux, while the voltage across it is numerically equal to the magnetic force.

The modeling of hysteresis phenomena and eddy currents in dynamic behavior is more difficult. We developed an accurate model of eddy currents, their power loss and their electromotive force, through an equivalent electric lumped circuit [5,6]. The model is based on the Maxwell's laws only. The parameters of the model are taken from the ferromagnetic material manufacturer's data sheet: the nonlinear first magnetization B-H characteristic; the specific iron losses given for a reference frequency and a reference value of the magnetic flux density (commonly 50 Hz and 1 Tesla for cold laminated steel sheet). Thus, the geometric dimensions of the ferromagnetic path are given as model parameters.

The model considers an equivalent eddy current, obtained with a computing chain according to the Faraday's law (which gives us the electromotive force in the core driven by the time-dependent magnetic flux) and the Ohm's law (which gives us the eddy current density, driven by the above-obtained electromotive force). The equivalent eddy current is obtained through integration on the entire domain. It is forced to cross an equivalent linear electric resistance, which dissipates an amount of heat numerically equal to the real eddy current losses. Finally, the eddy current magnetomotive force is opposed to the main magnetomotive force of the ferromagnetic path. The principle described above was detailed in [5,8].

The computation chains of the ferromagnetic piece model are synthesized in the equivalent diagram of fig. 1, built in Simulink. It corresponds to a ferromagnetic piece, crossed by a homogenous-assumed magnetic field, excited by a certain magnetic force u_m, delivered by the signal generator 1. The magnetic force is scaled according to the length of the modeled piece l_{Fe} (see the block 3), in order to obtain the magnetic field $H = u_m / l_{Fe}$, as input quantity of the lookup table 4 that delivers the magnetic flux density B, according to the first magnetization characteristic. This last is multiplied by the cross section of the core piece S_{Fe} (see block 5) in order to obtain the magnetic flux $\varphi = B \cdot S_{fe}$. The derivative of the magnetic flux is performed (block 6) in order to obtain the electric field density E, according to the Faraday's law, then the current density according to the Ohm's law and the equivalent eddy current (block 7). The equivalent eddy current corresponds to a magnetomotive force that opposes to the main one (block 2). Thus, it gives the instantaneous eddy current losses according to the Joule's law (blocks 8 and 9). The mean value of instantaneous power losses is computed (blocks 10 and 11) and could be displayed (block 14). Thus, other relevant quantities can be displayed as time domain functions: the excitation magnetomotive force (block 12), the magnetic flux (block 13), the equivalent eddy current (block 16) and the instantaneous eddy current power losses (block 15).

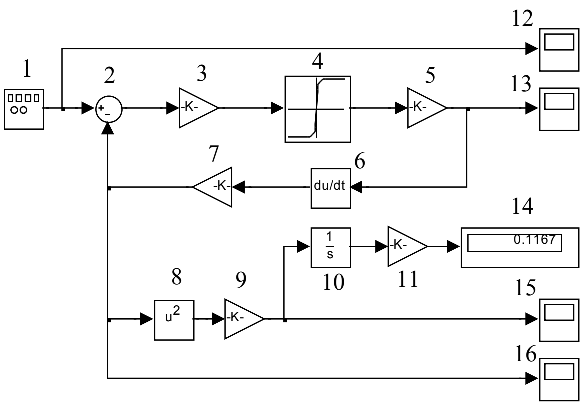

Figure 1. Computation chains of the ferromagnetic piece model

The above described model was implemented as SPICE subcircuit, in order to be included in any application of time-domain circuit simulation. The SPICE subcircuit is detailed in [5]. Such models are assembled according to the ferromagnetic core topology.

A winding crossed by a certain current is modeled according to the Ampere's law that explains the correspondence between the Ampere-turns and the excitation magnetomotive force. On the other hand, the core magnetic field induces an electromotive force into the winding, according to the Faraday's law; it is the reaction electromotive force that opposes to the main voltage across the winding terminals. The winding model is detailed in [6].

3. SIMULATION TOOL

The simulation tool includes an accurate model of the smoothing inductor in the complex diagram of the whole chain containing the line impedance, power converter structure and the load. It is implemented using the time-domain circuit simulator SPICE, version ICAP/4 from Intusoft®, where the model of the inductor was built as described in the previous section. The model parameters are the constructive parameters of the ferromagnetic core (i.e. material characteristics and geometric properties, including the airgap length), as well as the winding characteristics (number of turns and electric resistance). Any working parameter can be chosen as output quantity, including main magnetic flux, eddy current losses or magnetization loops, as results of the transient analysis [5,7].

A generic diagram containing the inductor model as part of the energy conversion equipment is shown in fig. 2. The inductor model is detailed and highlighted by the dashed line, where the left side correspond to the winding, while the right side correspond to the magnetic core. A common DC reactor of laminated E+I steel sheets, with one winding placed on the central leg, has been chosen. On the core model one see the main leg with the ferromagnetic reluctance (as the subcircuit X1), the airgap (X0G), the ampere-turns as output of the current controlled voltage source (V_I1), controlled by the winding current, and the measure point of the main magnetic flux (FLUX1). The winding model considers the counter electromotive force of $e = -N(\mathrm{d}\varphi/\mathrm{d}t)$, computed through the unity inductor (L2) used as derivative element.

The network short-circuit parameters (R_{netw}, L_{netw}), as well as a resistive load (R_{load}) were considered. The sideways legs are modeled in the same manner, but deliberately missing the ampere-turns.

This version of SPICE was not chosen at random, because it contains an optimization tool related to user-defined objective functions [9].

The optimizer searches the optimal value of a parameter that assures the maximum of the objective function. In our application, the objective is the optimal smoothing effect of the inductor, which is equivalent to the minimum value of the ripple load current: $I_r[\%] = (I_{\max} - I_{\min}) / I_{\text{average}} \cdot 100$.

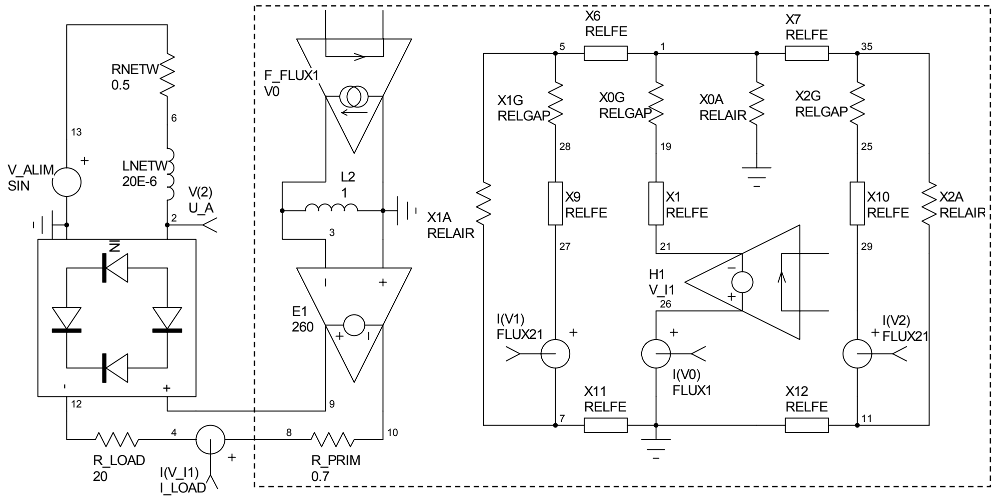

Figure 2. Circuit diagram built with SPICE

Therefore, the inverse of the ripple current is chosen as objective function in the SPICE optimizer: $ObjFcn = I_{average} / (I_{max} - I_{min})$. The parameter is the airgap length, which imposes the magnetic reluctance. As simulation result, optimal value of the smoothing effect is obtained as consequence of the optimal airgap length. The implicit number of iterations of the SPICE optimizer is limited to 10 [9].

4. EXAMPLE

The chosen example uses the generic diagram of fig. 2, where particular quantities were assigned. The power converter is a full-wave rectifier that supplies the resistive load.

The results of the optimization were assembled as in fig. 3 for three different levels of the load, our proposed objective being accomplished. It is noticeable that same value of the current ripple was obtained for any load level. The optimal airgap was searched in the domain of 0.25mm – 2.5mm, corresponding to a magnetic reluctance of $(10^5 \div 10^6)\,\mathrm{A \cdot Wb^{-1}}$.

The magnetization cycles of the main leg of the inductor were built during the optimization process and shown in fig. 4 for the rated value of the load, where the curve 8 corresponds to the optimal length of the airgap. The corresponding load currents represented in the time domain are shown in fig. 5, which does not require any comment.

The content of the output file is shown in fig. 6, where the iteration counter is located on the first column, followed by the airgap reluctance and the objective function (see the inverse of the relative value of the current ripple).

The eddy current losses were chosen as output quantity too (see the last column). The optimal result (see count no. 9) corresponds to an airgap of 0.9mm and a ripple current of 33%.

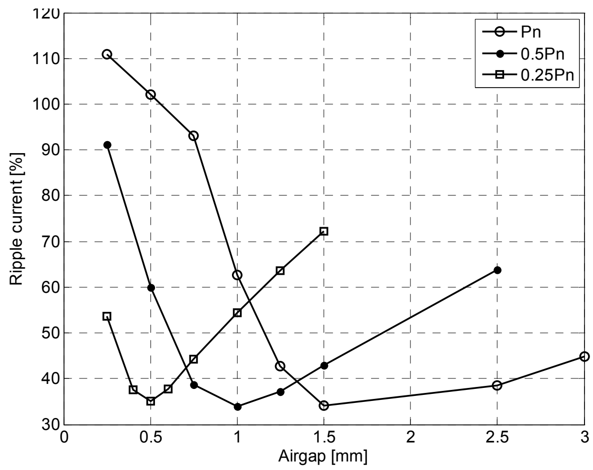

Figure 3. Optimal values of the inductor airgap

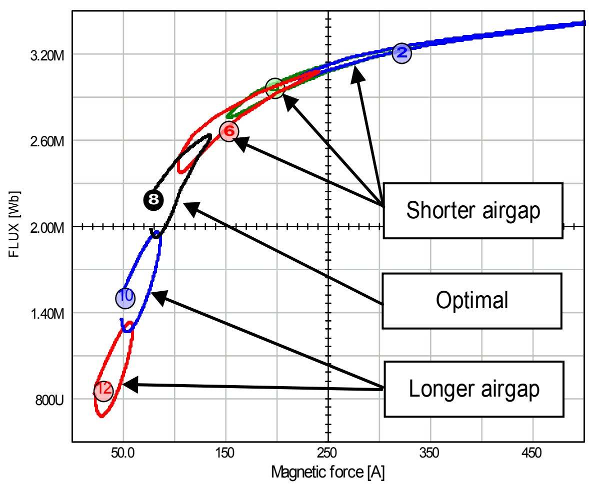

Figure 4. Magnetization characteristics of the main leg at rated load level

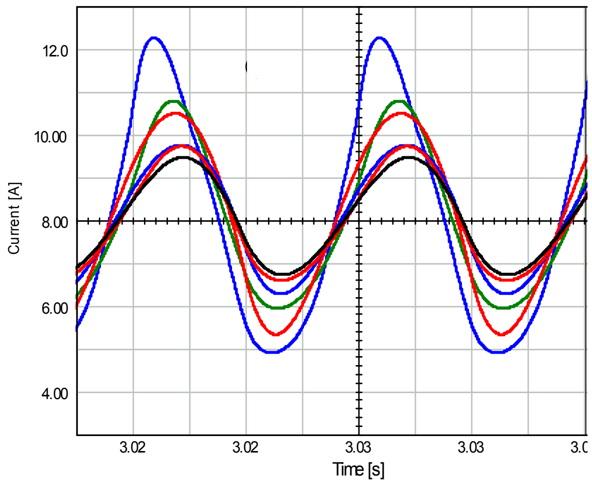

Figure 5. Simulated time-domain load current for different values of the airgap, at rated load level

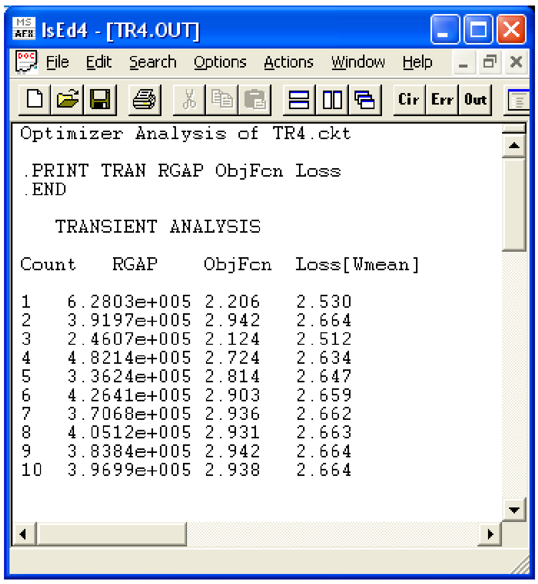

Figure 6. Content of the SPICE optimizer output file

5. CONCLUSIONS

A reliable design tool has been adapted in order to solve a real optimization problem, where the phenomena related to the DC-biased ferromagnetic core (i.e. nonlinearity, saturation and eddy currents) are difficult to be studied and can cause unpredictable behaviors. The implementation in SPICE allows treating the coupled electric/magnetic problem in the easiest manner. Many experimental essays were verified the developed optimization tool.

Obviously, the principle used by the above presented method may be extended for other design application for inductors, transformers or motors. Almost any optimization parameter or objective function could be considered.

6. REFERENCES

[1] F. Fiorillo, L. R. Dupré, "Comprehensive Model of Magnetization Curve, Hysteresis Loops, and Losses in Any Direction in Grain-Oriented Fe-Si", IEEE Transactions on Magnetics, Vol. 38, no. 3, May 2002, pp. 1467 – 1476;

[2] J.H. Chan, A. Vladimirescu, X.C. Gao, P. Liebmann, J. Valainis, "Nonlinear Transformer Model for Circuit Simulation", IEEE Transactions on Computer-Aided Design, vol. 10, no. 4, April 1991, pp. 476-482;

[3] H.G. Brachtendorf, C. Eck, R. Laur, "Macromodeling of Hysteresis Phenomena with SPICE", IEEE Transactions on Circuits and Systems - II: Analog and Digital Signal Processing, vol. 44, no. 5, May 1997, pp. 378-388;

[4] M. O'Hara, "Modeling Non-Ideal Inductors in SPICE", www.intusoft.com;

[5] L. Mandache, D. Topan, K. Al-Haddad, "Modeling of Nonlinear Ferromagnetic Cores", Revue Roumaine des Sciences Techniques, série Électrotechnique et Énergétique, Tome 53, No. 4, Bucarest, 2008, pp. 403-412;

[6] L. Mandache, K. Al-Haddad, "An Accurate Design Tool for Filter Inductors", The 33rd Annual Conference of the IEEE Industrial Electronics Society – IECON 2007, Taipei, Taiwan, November 5-8, 2007;

[7] D. Topan, L. Mandache, Chestiuni speciale de analiza circuitelor electrice, Ed. Universitaria, Craiova, 2007;

[8] L. Mandache, D. Topan, "Managing Eddy Current Losses and Ferromagnetic Material Nonlinearities in Distorting Regimes", IEEE International Conference of Electrial Machines and Drives – IEMDC 2009, May 3-6, 2009, Miami, pp. 1764-1769;

[9] ***, ICAP/4 IsSpice4 Users's Guide, Intusoft, San Pedro, CA, 1995.

Acknowledgement

This work was supported by the Romanian Ministry of Education and Research – National Research and Development Program PN II, especially through the research grants PCE 539/2008 and PC 21076/2007.